

Yukawa unification : MSSM at large $\tan \beta$

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Abstract. Talk given at PASCOS 2012, Merida, Mexico describing work in progress in collaboration with Archana Anandakrishnan, Christopher Plumberg and Akin Wingerter.

1. Introduction

In this talk we discuss SO(10) Yukawa unification and its ramifications for phenomenology. The initial constraints come from fitting the top, bottom and tau masses, requiring large $\tan \beta \sim 50$ and particular values for soft SUSY breaking parameters. We will show that this leads to a spectrum of squark and slepton masses with the first two families heavy while the third family is significantly lighter, i.e. an inverted scalar mass hierarchy. In addition, gauginos should be observable at the LHC. We perform a global χ^2 analysis, fitting the recently observed ‘Higgs’ with mass of order 125 GeV in addition to fermion masses and mixing angles and several flavor violating observables.

Fermion masses and mixing angles are manifestly hierarchical. The simplest way to describe this hierarchy is with Yukawa matrices which are also hierarchical. Moreover the most natural way to obtain the hierarchy is in terms of effective higher dimension operators of the form

$$W \supset 16_3 \ 10 \ 16_3 + 16_3 \ 10 \ \frac{45}{M} \ 16_2 + \dots \quad (1)$$

This version of SO(10) models has the nice features that it only requires small representations of SO(10), has many predictions and can, in principle, find an UV completion in string theory. There are a long list of papers by authors such as Albright, Anderson, Babu, Barr, Barbieri, Berezhiani, Blazek, Carena, Chang, Dermisek, Dimopoulos, Hall, Masiero, Murayama, Pati, Raby, Romanino, Rossi, Starkman, Wagner, Wilczek, Wiesenfeldt, and Willenbrock which have followed this line of model building.

The only renormalizable term in W is $\lambda \ 16_3 \ 10 \ 16_3$ which gives Yukawa coupling unification

$$\lambda = \lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \quad (2)$$

at M_{GUT} . Note, one CANNOT predict the top mass due to large SUSY threshold corrections to the bottom and tau masses, as shown in [1]. These corrections are of the form

$$\delta m_b/m_b \propto \frac{\alpha_3 \ \mu \ M_{\tilde{g}} \ \tan \beta}{m_b^2} + \frac{\lambda_t^2 \ \mu \ A_t \ \tan \beta}{m_t^2} + \log \text{ corrections.} \quad (3)$$

So instead we use Yukawa unification to predict the soft SUSY breaking masses!! In order to fit the data, we need

$$\delta m_b/m_b \sim -2\%. \quad (4)$$

We take $\mu M_{\tilde{g}} > 0$, thus we need $\mu A_t < 0$. For a short list of references on this subject, see [2, 3].

Given the following GUT scale boundary conditions – universal squark and slepton masses, m_{16} , universal cubic scalar parameter, A_0 , universal gaugino masses, $M_{1/2}$, and non-universal Higgs masses [NUHM] or ‘just so’ Higgs splitting, m_{H_u} , m_{H_d} or $m_{H_{u(d)}}^2 = m_{10}^2[1 - (+)\Delta_{m_H}^2]$, we find that fitting the top, bottom and tau mass forces us into the region of SUSY breaking parameter space with

$$A_0 \approx -2m_{16}, \quad m_{10} \approx \sqrt{2} m_{16}, \quad m_{16} > \text{few TeV}, \quad \mu, M_{1/2} \ll m_{16}; \quad (5)$$

and, finally,

$$\tan \beta \approx 50. \quad (6)$$

In addition, radiative electroweak symmetry breaking requires $\Delta_{m_H}^2 \approx 13\%$, with roughly half of this coming naturally from the renormalization group running of neutrino Yukawa couplings from M_G to $M_{N_\tau} \sim 10^{13}$ GeV [2].

It is very interesting that the above region in SUSY parameter space results in an inverted scalar mass hierarchy at the weak scale with the third family scalars significantly lighter than the first two families [4]. This has the nice property of suppressing flavor changing neutral current and CP violating processes.

2. Heavy squarks and sleptons

Considering the theoretical and experimental results for the branching ratio $BR(B \rightarrow X_s \gamma)$, we argue that $m_{16} \geq 8$ TeV. The experimental value $BR(B \rightarrow X_s \gamma)_{\text{exp}} = (3.55 \pm 0.26) \times 10^{-4}$, while the NNLO Standard Model theoretical value is $BR(B \rightarrow X_s \gamma)_{\text{th}} = (3.15 \pm 0.23) \times 10^{-4}$. The amplitude for the process $B \rightarrow X_s \gamma$ is proportional to the Wilson coefficient, C_7 . $C_7 = C_7^{SM} + C_7^{SUSY}$ and, in order to fit the data, we see that $C_7 \approx \pm C_7^{SM}$. Thus $C_7^{SUSY} \approx -2C_7^{SM}$ or $C_7^{SUSY} \approx 0$. The dominant SUSY contribution to the branching ratio comes from a stop - chargino loop with $C_7^{SUSY} \sim C_7^{\chi^+} \sim \frac{\mu A_t}{\tilde{m}^2} \tan \beta \times \text{sign}(C_7^{SM})$ (see Fig. 1). Hence, in our case $C_7 \approx -C_7^{SM}$.

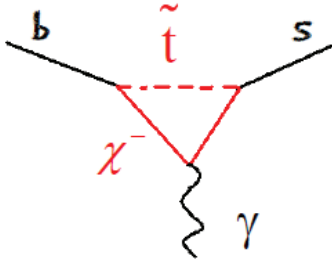


Figure 1. Dominant contribution to the process $b \rightarrow s \gamma$ in the MSSM.

Recent LHCb data on the $BR(B \rightarrow K^* \mu^+ \mu^-)$ now favors $C_7 \approx +C_7^{SM}$ [6]. See Fig. 2. This tension between the processes $b \rightarrow s \gamma$ and $b \rightarrow s \ell^+ \ell^-$ was already discussed by Albrecht et al. [5]. In order to be consistent with this data one requires $C_7^{\chi^+} \approx 0$ or $C_7 \approx C_7^{SM} + C_7^{SUSY} \approx +C_7^{SM}$ and therefore $m_{16} \geq 8$ TeV.

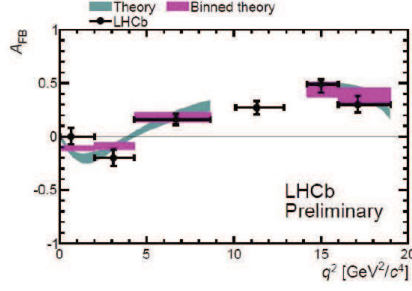


Figure 2. The forward-backward asymmetry for the process $B \rightarrow K^* \mu^+ \mu^-$ measured by LHCb.

3. Light Higgs mass

An approximate formula for the light Higgs mass is given by [7]

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \left(\frac{M_{SUSY}^2}{m_t^2} \right) + \frac{X_t^2}{M_{SUSY}^2} \left(1 - \frac{X_t^2}{12M_{SUSY}^2} \right) \right] \quad (7)$$

where $X_t = A_t - \mu/\tan\beta$. The light Higgs mass is maximized as a function of X_t for $X_t/M_{SUSY} = \sqrt{6}$, referred to as maximal mixing. Hence we see that for large values of A_t and M_{SUSY} it is quite easy to obtain a light Higgs mass of order 125 GeV.

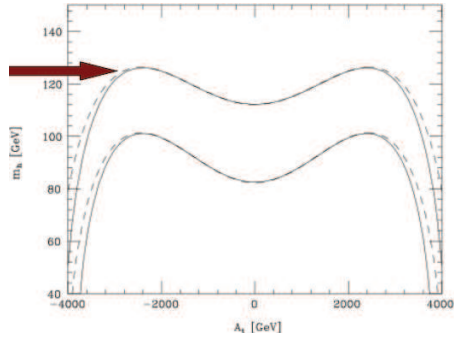


Figure 3. Light Higgs mass as a function of A_t for two values of $\tan\beta$. The upper curve corresponds to $\tan\beta \sim 50$. The arrow corresponds to maximal mixing.

4. $B_s \rightarrow \mu^+ \mu^-$

In this section we argue that the light Higgs boson must be Standard Model-like. To do this we show that the CP odd Higgs boson, A , must have mass greater than ~ 1 TeV and as a consequence this is also true for the CP even Higgs boson, H , and the charged Higgs bosons, H^\pm , as well. This is the well-known decoupling limit in which the light Higgs boson couples to matter just like the Standard Model Higgs.

Consider the branching ratio $BR(B_s \rightarrow \mu^+ \mu^-)$ which in the Standard Model is $\sim 3 \times 10^{-9}$. In the MSSM this receives a contribution proportional to $\sim \frac{\tan^6\beta}{m_A^4}$. Recent experimental results give [8]

$$CDF : 1.8(+1.8, -0.9) \times 10^{-8} \text{ (95\%CL) with } 7fb^{-1} \quad (8)$$

$$LHCb \text{ bound : } < 4.5 \times 10^{-9} \text{ (95\%CL) with } 1fb^{-1}. \quad (9)$$

These two results seem to be inconsistent, so we will choose to try and satisfy the LHCb data which is also consistent with results from CMS. Since we have $\tan\beta \sim 50$, our only choice is to take the CP odd Higgs mass to be large with $m_A \geq 1$ TeV. Hence the light Higgs is SM-like.

5. 3 Family Model

The previous results depended solely on $SO(10)$ Yukawa unification for the third family. We now consider a complete three family $SO(10)$ model for fermion masses and mixing, including neutrinos [9, 5]. The model also includes a $D_3 \times [U(1) \times \mathbb{Z}_2 \times \mathbb{Z}_3]$ family symmetry which is necessary to obtain a predictive theory of fermion masses by reducing the number of arbitrary parameters in the Yukawa matrices. In the rest of this talk we will consider the new results due to the three family analysis. We shall consider the superpotential generating the effective fermion Yukawa couplings. We then perform a global χ^2 analysis, including precision electroweak data which now includes both neutral and charged fermion masses and mixing angles.

The superspace potential for the charged fermion sector of this model is given by:

$$W_{ch.fermions} = 16_3 \ 10 \ 16_3 + 16_a \ 10 \ \chi_a \quad (10)$$

$$+ \bar{\chi}_a (M_\chi \chi_a + 45 \frac{\phi_a}{M} 16_3 + 45 \frac{\tilde{\phi}_a}{M} 16_a + \mathbf{A} 16_a)$$

where 45 is an $SO(10)$ adjoint field which is assumed to obtain a VEV in the B – L direction; and M is a linear combination of an $SO(10)$ singlet and adjoint. Its VEV $M_0(1 + \alpha X + \beta Y)$ gives mass to Froggatt-Nielsen states. Here X and Y are elements of the Lie algebra of $SO(10)$ with X in the direction of the $U(1)$ which commutes with $SU(5)$ and Y the standard weak hypercharge; and α, β are arbitrary constants which are fit to the data.

$$\phi_a, \quad \tilde{\phi}_a, \quad A, \quad (11)$$

are $SO(10)$ singlet ‘flavon’ fields, and

$$\bar{\chi}_a, \quad \chi_a \quad (12)$$

are a pair of Froggatt-Nielsen states transforming as a $\overline{16}$ and 16 under $SO(10)$. The ‘flavon’ fields are *assumed* to obtain VEVs of the form

$$\langle \phi_a \rangle = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad \langle \tilde{\phi}_a \rangle = \begin{pmatrix} 0 \\ \tilde{\phi}_2 \end{pmatrix}. \quad (13)$$

After integrating out the Froggatt-Nielsen states one obtains the effective fermion mass operators in Fig. 4. We then obtain the Yukawa matrices for up and down quarks, charged leptons and

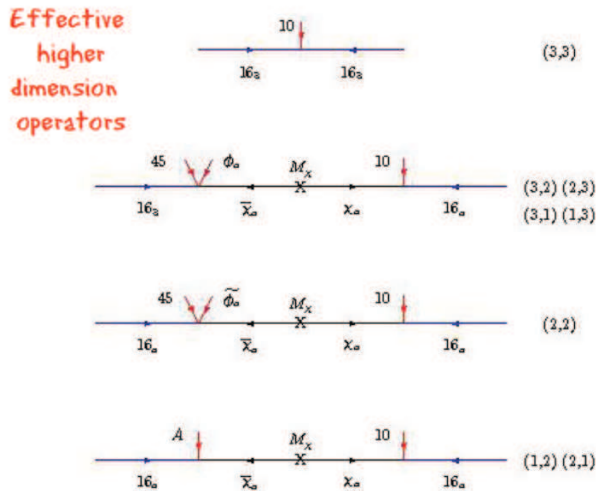


Figure 4. The effective fermion mass operators obtained after integrating out the Froggatt-Nielsen massive states.

neutrinos given in Fig. 5. These matrices contain 7 real parameters and 4 arbitrary phases.

$$\begin{aligned}
Y_u &= \begin{pmatrix} 0 & \epsilon' \rho & -\epsilon \xi \\ -\epsilon' \rho & \tilde{\epsilon} \rho & -\epsilon \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda \\
Y_d &= \begin{pmatrix} 0 & \epsilon' & -\epsilon \xi \sigma \\ -\epsilon' & \tilde{\epsilon} & -\epsilon \sigma \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda \\
Y_e &= \begin{pmatrix} 0 & -\epsilon' & 3 \epsilon \xi \\ \epsilon' & 3 \tilde{\epsilon} & 3 \epsilon \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda \\
Y_\nu &= \begin{pmatrix} 0 & -\epsilon' \omega & \frac{3}{2} \epsilon \xi \omega \\ \epsilon' \omega & 3 \tilde{\epsilon} \omega & \frac{3}{2} \epsilon \omega \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda
\end{aligned}$$

Figure 5. The Yukawa matrices obtained from the effective fermion mass operators after taking into account the flavon VEVs.

Note, the superpotential (Eqn. 10) has many arbitrary parameters. However, at the end of the day the effective Yukawa matrices have many fewer parameters. This is good, because we then obtain a very predictive theory. Also, the quark mass matrices accommodate the Georgi-Jarlskog mechanism, such that $m_\mu/m_e \approx 9m_s/m_d$.

We then add 3 real Majorana mass parameters for the neutrino see-saw mechanism. The anti-neutrinos get GUT scale masses by mixing with three $SO(10)$ singlets $\{N_a, a = 1, 2; N_3\}$ transforming as a D_3 doublet and singlet respectively. The full superpotential is given by $W = W_{ch.fermions} + W_{neutrino}$ with

$$\begin{aligned}
W_{neutrino} &= \overline{16} (\lambda_2 N_a 16_a + \lambda_3 N_3 16_3) \\
&+ \frac{1}{2} (S_a N_a N_a + S_3 N_3 N_3).
\end{aligned} \tag{14}$$

We assume $\overline{16}$ obtains a VEV, v_{16} , in the right-handed neutrino direction, and $\langle S_a \rangle = M_a$ for $a = 1, 2$ and $\langle S_3 \rangle = M_3$. The effective neutrino mass terms are given by

$$W = \nu m_\nu \bar{\nu} + \bar{\nu} V N + \frac{1}{2} N M_N N \tag{15}$$

with

$$V = v_{16} \begin{pmatrix} 0 & \lambda_2 & 0 \\ \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}, \quad M_N = \text{diag}(M_1, M_2, M_3) \tag{16}$$

all assumed to be real. Finally, upon integrating out the heavy Majorana neutrinos we obtain the 3×3 Majorana mass matrix for the light neutrinos in the lepton flavor basis given by

$$\mathcal{M} = U_e^T m_\nu M_R^{-1} m_\nu^T U_e, \tag{17}$$

where the effective right-handed neutrino Majorana mass matrix is given by:

$$M_R = V M_N^{-1} V^T \equiv \text{diag}(M_{R1}, M_{R2}, M_{R3}), \tag{18}$$

with

$$M_{R1} = (\lambda_2 v_{16})^2 / M_2, \quad M_{R2} = (\lambda_2 v_{16})^2 / M_1, \quad M_{R3} = (\lambda_3 v_{16})^2 / M_3. \tag{19}$$

6. Global χ^2 analysis

Just in the fermion mass sector we can see that the theory is very predictive. We have 15 charged fermion and 5 neutrino low energy observables given in terms of 11 arbitrary Yukawa parameters and 3 Majorana mass parameters. Hence there are 6 degrees of freedom in this

Table 1. Parameters entering the global χ^2 analysis.

<i>Sector</i>	#	<i>Parameters</i>
<i>gauge</i>	3	$\alpha_G, M_G, \epsilon_3$
<i>SUSY (GUT scale)</i>	5	$m_{16}, M_{1/2}, A_0, m_{H_u}, m_{H_d}$
<i>textures</i>	11	$\lambda, \epsilon, \epsilon', \rho, \sigma, \tilde{\epsilon}, \xi$
<i>neutrino</i>	3	M_{R1}, M_{R2}, M_{R3}
<i>SUSY (EW scale)</i>	2	$\mu, \tan \beta$

sector of the theory. However in order to include the complete MSSM sector we perform the global χ^2 analysis with 24 arbitrary parameters at the GUT scale given in Table 1. Note, this is to be compared to the 27 arbitrary parameters in the Standard Model or the 32 parameters in the CMSSM.

In 2007, Albrecht et al. [5] performed a global χ^2 analysis of this theory. Two of the tables from their paper are exhibited in Fig. 6. This analysis included 27 low energy observables and a reasonable fit to the data was only found for $m_{16} = 10$ TeV. Note, the Higgs mass was predicted to be 129 GeV. There is now a discovery by CMS and ATLAS of a boson with mass of order

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.403	80.6	0.5
M_Z	91.1876	90.7	1.1
$G_F \times 10^5$	1.16637	1.16	0.3
$1/\alpha_{em}$	137.036	136.8	0.4
$\alpha_s(M_Z)$	0.1176	0.117	0.2
M_t	170.9	170.6	0.2
$m_b(m_b)$	4.2	4.22	0.3
$m_c(m_b)$	1.25	1.14	1.2
$m_s(2 \text{ GeV})$	0.095	0.107	0.5
$m_d(2 \text{ GeV})$	0.005	0.00741	1.2
$m_u(2 \text{ GeV})$	0.00225	0.00461	3.1
M_τ	1.777	1.78	0.1
M_μ	0.10566	0.106	0.1
M_e	0.000511	0.000511	0.0
$ V_{us} $	0.2258	0.225	0.6
$ V_{ub} \times 10^3$	4.1	3.26	2.1
$ V_{cb} $	0.0416	0.0416	0.1
$\sin 2\beta$	0.675	0.639	1.4
$\Delta m_{31}^2 \times 10^{21}$	2.6	2.6	0.0
$\Delta m_{21}^2 \times 10^{23}$	7.9	7.9	0.0
$\sin^2 2\theta_{12}$	0.852	0.852	0.0
$\sin^2 2\theta_{23}$	0.996	1.0	0.2
$\epsilon_K \times 10^3$	2.229	2.33	0.4
$\text{BR}(B \rightarrow X_s \gamma) \times 10^4$	3.55	2.86	1.3
$\text{BR}(B \rightarrow X_s \ell^+ \ell^-) \times 10^6$	1.6	1.62	0.0
$\Delta M_s / \Delta M_d$	35.05	31.1	1.1
$\text{BR}(B^+ \rightarrow \tau^+ \nu) \times 10^4$	1.31	0.517	1.7
total χ^2 : 27.4			

m_{16}	10000
μ	1200
$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^8$	2.1
\hat{s}_0	0.14
$\text{BR}(\mu \rightarrow e \gamma) \times 10^{13}$	0.0026
$\delta a_\mu^{\text{SUSY}} \times 10^{10}$	+0.52
M_{h_0}	129
M_A	842
$m_{\tilde{t}_1}$	1903
$m_{\tilde{b}_1}$	2366
$m_{\tilde{\tau}_1}$	3933
$m_{\tilde{\chi}_1^0}$	60
$m_{\tilde{\chi}_1^\pm}$	120
$m_{\tilde{g}}$	506

Required $C_7 = +C_7^{\text{SM}}$

Figure 6. The results obtained by Albrecht et al. for $m_{16} = 10$ TeV.

125 GeV. This may well be the Higgs boson with Standard Model couplings, but further data is needed before such a conclusion can be confirmed. In the mean time we shall assume it is the lightest Higgs boson of the MSSM. In this case, we must conclude (based on our analysis) that it must look very much like the Standard Model Higgs boson, since as can be seen from Fig. 6, the CP odd Higgs mass, $m_A = 842$ GeV, so the theory is in the Higgs decoupling limit.

In this work we have decided to extend the analysis of Albrecht et al. to values of $m_{16} \geq 10$ TeV, including more low energy observables such as the light Higgs mass, the neutrino mixing angle θ_{13} and lower bounds on the gluino and squark masses coming from recent data. This work is in progress in collaboration with Archana Anandakrishnan, Christopher Plumberg and Akin Wingerter, along with significant help from Radovan Dermisek and Aditi Raval. We perform a three family global χ^2 analysis. We are using the code developed by Radovan Dermisek to renormalize the parameters in the theory from the GUT scale to the weak scale, perform electroweak symmetry breaking and calculate squark, slepton, gaugino masses, as well as quark and lepton masses and mixing angles. We also use the Higgs code of Pietro Slavich (suitably revised for our particular scalar spectrum) to calculate the light Higgs mass and SUSY_Flavor_v2.0 [10] to evaluate flavor violating B decays.

There are 24 arbitrary parameters defined mostly at the GUT scale and run down to the weak scale where the χ^2 function is evaluated. However the value of m_{16} has been kept fixed in our analysis, so that we can see the dependence of χ^2 on this input parameter. Thus with 23 arbitrary parameters we fit 37 observables, giving 14 degrees of freedom. The χ^2 function has been minimized using the CERN package, MINUIT. This work is on going so we just present the complete results for one value of $m_{16} = 20$ TeV (see Table 2). The fit is quite good with $\chi^2/d.o.f. = 1.8$. However, note that we have not taken into account correlations in the data, so we will just use χ^2 as a indicator of the rough goodness of the fit. In Table 3 we see that the value of χ^2 decreases as m_{16} increases, but our analysis shows that the $m_{16} \sim 20$ TeV minimizes χ^2 , i.e. we have found that χ^2 slowly increases for $m_{16} > 20$ TeV.

7. Conclusion and plans for the future

We have presented an analysis of a theory satisfying Yukawa unification and large $\tan \beta$. The results are encouraging but as usual there are some good and some bad features.

Some of the good features are -

- gauge coupling unification is satisfied
- the Higgs mass is of order 125 GeV and Standard Model like
- there is an inverted scalar mass hierarchy, with the following consequence at the LHC -
- gluinos predominantly decay via $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0$, $t \bar{b} \tilde{\chi}^-$, $b \bar{b} \tilde{\chi}^0$, etc.

And bad features -

- fine-tuned by at least 0.1 %
- and gluinos are light.

Work in progress -

- We would like to understand why χ^2 increases for values of $m_{16} > 20$ TeV or is there an upper bound on m_{16} ?
- The gaugino masses are small. We want to evaluate the χ^2 dependence as a function of the gluino mass or, in other words, ascertain the sensitivity of χ^2 on varying the gaugino masses?
- Finally, we would like to consider alternative sets of boundary conditions at the GUT scale which may be consistent with Yukawa unification. In particular, we will consider the so-called “DR3” scheme and non-universal gaugino masses as may be obtained with (a) non-trivial gauge kinetic functions or (b) “mirage mediation.”

In the “DR3” scheme [11] we have SO(10) boundary conditions at M_{GUT} , however the third family scalar masses are taken to be smaller than the first two, i.e. $m_{16}^{(3)} \leq m_{16}^{(1,2)}$. In addition, Higgs doublet mass splitting is accomplished with a $U(1)_X$ D-term, D_X , where $U(1)_X$ is the

Table 2. Result of global χ^2 analysis for m_{16} fixed at 20 TeV.

Observable	Fit value	Exp. value	Pull	Sigma
M_Z	91.1876	91.1876	0.0000	0.0912
M_W	80.7955	80.4360	0.8938	0.4022
$1/\alpha_{em}$	136.5851	137.0360	0.6580	0.6852
$G_\mu \times 10^5$	1.1766	1.1664	0.8805	0.0117
α_3	0.1184	0.1184	0.0642	0.0007
M_t	173.2432	172.9000	0.3177	1.0800
$m_b(m_b)$	4.3155	4.1900	0.6973	0.1800
m_τ	1.7766	1.7770	0.0484	0.0089
$M_b - M_c$	3.4285	3.4300	0.0300	0.0500
$m_c(m_c)$	1.1723	1.2900	1.0697	0.1100
m_s	0.0969	0.1000	0.1039	0.0300
m_d/m_s	0.0693	0.0521	2.5690	0.0067
$1/Q^2$	0.0019	0.0019	0.3475	0.0001
M_μ	0.1056	0.1057	0.0386	0.0005
$M_e \times 10^4$	5.1125	5.1100	0.0978	0.0255
$ V_{us} $	0.2250	0.2252	0.2407	0.0009
$ V_{cb} $	0.0412	0.0406	0.4702	0.0013
$ V_{ub} \times 10^3$	3.2245	3.8900	1.5124	0.4400
$ V_{td} \times 10^3$	8.9128	8.4000	0.8547	0.6000
$ V_{ts} $	0.0404	0.0429	0.9750	0.0026
$\sin 2\beta$	0.6370	0.6730	1.5642	0.0230
ϵ_K	0.0021	0.0022	0.3631	0.0002
$\Delta M_{Bs}/\Delta M_{Bd}$	31.7861	35.0000	0.4439	7.2400
$\Delta M_{Bd} \times 10^{13}$	4.2657	3.3370	1.3944	0.6660
$m_{21}^2 \times 10^5$	7.5243	7.5400	0.0340	0.4600
$m_{31}^2 \times 10^3$	2.4708	2.4600	0.0637	0.1700
$\sin^2 \theta_{12}$	0.2984	0.3070	0.2445	0.0350
$\sin^2 \theta_{23}$	0.4390	0.3980	0.5323	0.0770
$\sin^2 \theta_{13}$	0.0132	0.0245	1.7062	0.0066
M_h	124.80	125.30	0.1664	3.0000
$BR(B \rightarrow X_s \gamma) \times 10^4$	3.4988	3.5500	0.0368	1.3900
$BR(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	4.2909	4.5000	0.0000	1.0000
$BR(B_d \rightarrow \mu^+ \mu^-) \times 10^{10}$	1.3112	14.0000	0.0000	10.0000
$BR(B \rightarrow \tau \nu) \times 10^5$	6.8017	16.5000	1.0428	9.3000
$BR(B \rightarrow K^* \mu^+ \mu^-)(\text{low}) \times 10^8$	5.0639	4.2000	0.3199	2.7000
$BR(B \rightarrow K^* \mu^+ \mu^-)(\text{high}) \times 10^8$	7.5709	6.3000	0.4707	2.7000
$q_0^2(B \rightarrow K^* \mu^+ \mu^-)$	4.6274	4.9000	0.2097	1.3000
Total χ^2	24.2			

Table 3. Results for the global χ^2 analysis with 3 different values of $m_{16} = 10, 15, 20$ TeV.

m_{16}	10 TeV	15 TeV	20 TeV
A_0	-20 TeV	-30 TeV	-41 TeV
μ	517	900	766
$M_{1/2}$	270	200	169
χ^2	32.12	25.87	24.51
M_A	2357	2743	5970
$m_{\tilde{t}_1}$	1699	2952	3738
$m_{\tilde{b}_1}$	2087	3481	3702
$m_{\tilde{\tau}_1}$	3919	5932	7409
$m_{\tilde{\chi}_1^0}$	145	133	136
$m_{\tilde{\chi}_1^+}$	277	267	279
$m_{\tilde{g}}$	925	850	850

is found in $SO(10)/[SU(5) \times U(1)_X]$. Hence, $m_i^2 = Q_X^i D_X + (m_i^0)^2$ and the charges, Q_X^i , are given in Table 4.

Table 4. $U(1)_X$ charge and $SO(10)$ invariant mass.

	Q	U	D	L	E	N	H_u	H_d
Q_X^i	1	1	-3	-3	1	5	-2	2
m_i^0	m_{16}						m_{10}	

One possible scheme for obtaining non-universal gaugino masses was contemplated in [12] using a non-trivial gauge kinetic function with a chiral 54 dimensional representation of $SO(10)$ obtaining an F-term VEV, but NO scalar VEV. This gives gaugino masses in the ratio $M_3 : M_2 : M_1 = 1 : -3/2 : -1/2$. In addition they take $\mu < 0$ and $U(1)_X$ D-term splitting of squark, slepton and Higgs masses. In the end they obtain a totally different spectrum than with either “Just So” Higgs splitting or “DR3” splitting.

Finally, it has been shown that non-universal gaugino masses can be obtained with “mirage mediation” boundary conditions at M_{GUT} [13]. We would have gaugino masses given by

$$M_i(\mu)/g_i^2(\mu) = \left\{ 1 + \log(M_{Pl}/m_{3/2}) \frac{\alpha_{GUT} b_i}{4\pi} \alpha \right\} M_0/g_{GUT}^2 \quad (20)$$

where α is an arbitrary parameter fixing the ratio of the contributions of gravity vs anomaly mediation. In addition we would take $\mu < 0$ and $U(1)_X$ D-term splitting for scalars.

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